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Author(s): Christopher Morris
William C. Priedhorsky

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Muon Radiograph for Nuclear Material Detection

Christopher Morris* and W.C. Priedhorsky

Abstract

This is the final report of a Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL).

The threat of the detonation of a nuclear device in a major US city has prompted research aimed at providing more robust border surveillance for contraband nuclear material. The small amount of material needed to construct a nuclear device and the ease with which neutron and gamma ray signatures can be obscured with shielding makes this job difficult. We demonstrate a new technique which uses multiple scattering of cosmic ray muons to selectively detect high-z material in a background of normal cargo, and estimate the cost of implementing this technology for passenger vehicle traffic at all US border crossings. The advantages of this technique are that it is passive, does not any radiation dose above background, and is selective to high-z dense materials.

1. Background and Research Objectives

Of the threats posed by terrorist actions in the US, the most frightening is the detonation of a nuclear device in a major city. The toll of the deaths, destruction, and economic loss caused by such an action would be enormous. Recent events, along with scholarly evaluations of the probability of a terrorist group producing a nuclear weapon suggest the likelihood of such an event is significant.[1] The size of the risk and the enormous consequence of such an event have moved the US in the direction of trying to develop strategies to prevent it.

One of the strategies is to make nuclear material unavailable to terrorists by controlling the material at its source. Considerable US resources are being devoted to programs in the former Soviet Union states (FSU) to reduce the inventories of both highly enriched uranium and weapons grade plutonium (SNM), and to improve controls over these materials. Unfortunately, inventories and accounting of SNM is not complete enough to exclude the possibility that sufficient material to construct an improvised nuclear device is already available on the black market or in the hands of terrorist groups. Since it is unlikely that these efforts will be absolutely effective, other controls need to be implemented to achieve an adequate defense against terrorist nuclear devices.

* cmorris@lanl.gov

An additional reduction in risk can be obtained by increasing the likelihood of detection of illegal transport of these materials at transportation checkpoints, such as border crossings. US customs has begun using a set of radiation detectors and x-ray scanners at border crossing for this purpose. However, protecting against the movement of the nuclear materials is difficult because of the small quantities involved, and the ease with which the material can be shielded with small amounts of high-atomic charge (Z) material such as lead or tungsten.[1] A recent investigative report by ABC news illustrated the ease with which uranium can be transported across international borders.[2]

SNM produces gamma, neutron and alpha radioactivity above natural background levels. However, passive counting does not provide robust detection of hidden SNM because all of the signals can be obscured using a relatively small amount of high Z (lead), hydrogenous (polyethylene), and neutron absorbing (lithium or boron) shielding. More sophisticated counting techniques, such as directional gamma and neutron counting, and better energy resolution improve the sensitivity and limit some options for hiding SNM. However, because of practical counting time limits and natural background rates, small well shielded quantities can be moved through the best of passive systems.

X-ray radiography provides a method of examining cargo and transport vehicles for the presence of hidden material. New scanning x-ray machines in combination with neutron scatter and radiographic and x-ray back scatter might provide an approach for detecting shielded, hidden SNM. The potential doses to vehicle occupants and to operators limit this technology option to examining only a small fraction cross border traffic. Indeed the ABC report[3] illustrates how difficult this job is. A lead lined steel pipe containing about 7 kg of depleted uranium stored in a transportainer in the port of New York went undetected, in spite of being radiographed with x-rays.

2. Importance to LANL's Science and Technology Base and National R&D Needs

This work is directly tied to DOE and LANL missions in both non-proliferation and homeland defense.

3. Scientific Approach and Accomplishments

We have invented a new technique which is capable of passively detecting small quantities of shielded SNM in a short time by using the multiple scattering of cosmic ray muons as a radiographic probe.[4] This technique is selective to high-Z materials, both SNM and gamma-ray shielding materials.

When an energetic charged particle moves through material its trajectory results from the convolution of many small deflections due to Coulomb scattering from the charge of the atomic nuclei in the medium. The net angular and position deflection of the trajectory are very sensitive to the Z of the atomic nuclei. Charged particles are more strongly affected by materials that make good gamma ray shielding (lead and tungsten) and by SNM (uranium and plutonium) than by the materials that make up normal cargo such as people, paper, aluminum and steel.

The earth is continuously bombarded by energetic stable particles, mostly protons. These interact in the upper atmosphere because of the nuclear force, producing showers of particles that include many short lived particles called pions. The pions decay producing muons. Muons interact with matter primarily through the Coulomb force, and have no nuclear interaction. The Coulomb force removes energy from the muons more slowly than nuclear interactions. Consequently many of the muons arrive at the earth's surface, as penetrating, weakly interacting charged radiation. The flux at the earth's surface of muons in an energy and angular range useful for radiography is about 1 muon/cm^2/minute.[5]

Conventional radiography takes advantage of the absorption of penetrating radiation. For X-ray radiography,[6] the areal density of a pixel in the image is determined by its absorption or scattering of the incident beam: $N = N_0 e^{-\frac{L}{L_0}}$,[7] where L is the path length (areal density) through an object, and L_0 is the mean free path for scattering or absorption. The precision of radiographic measurements is limited by the Poisson counting statistics of the transmitted flux, $\frac{\Delta L}{L_0} = \frac{1}{\sqrt{N}}$. The maximum mean free path for photons in high-z elements occurs at a few MeV. The mean free path is approximately 25 gm/cm2 for all materials at this energy. This corresponds to less than 2 cm of lead. Penetrating objects of tens of L_0 requires very large incident dose.

An alternative is provided by a new kind of radiography.[8,9] Charged particles, such as protons or muons, interact with matter by multiple Coulomb scattering. The many small interactions add up to yield an angular deviation that follows a Gaussian distribution: $\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$.[10] The width of the distribution is related to the scattering material: $\theta_0 = \frac{13.5}{p\beta}\sqrt{\frac{L}{X}}$, where p is the particle momentum, β is the velocity divided by the velocity of light, and X is the radiation length. In a layer 10 cm thick, a 3 GeV muon will scatter with a mean angle 0 of 2.3 mrad in water ($X = 36$ cm), 11 mrad in iron ($X = 1.76$ cm), and 20 mrad in tungsten ($X = 0.56$ cm). If the muon scattering angle in an object can be measured, and it's momentum is known, then the path length, $\Delta L/L$ can be determined to a precision of $\frac{\Delta L}{L} = \sqrt{\frac{2}{N}}$, where N, the number of transmitted muons, is very nearly equal to the number incident. Thus each transmitted muon provides information about the thickness of the object.

Muon momentum information can be obtained inexpensively by measuring the multiple scattering resulting from several layers of scatterer of known thickness. This could be done by a scatter-detector sandwich that continues below the lowest detector plane. The precision in momentum determination would be $\frac{\Delta p}{p} = \frac{1}{\sqrt{2N_P}}$, where N_P is the number of scattering layers (the factor of two arises because x and y are measured independently). Even with just two planes, one obtains $\frac{\Delta p}{p} = 0.5$, which is adequate for a first-order momentum correction.

The flux of muons through a 10 cm cube of material in 30 seconds is sufficient to measure its thickness in radiation lengths to a precision of 14%. With these statistics a cube of tungsten can be distinguished from a cube of steel at the six standard deviation level.

Experimental demonstration

A set of position sensitive delay line readout drift chambers has been assembled to demonstrate this idea. Eight planes of detector above an object region and eight below were used to track muons through an 11 cm diameter by 5.7 cm high (9.9 kg of total weight) tungsten cylinder. Two plastic scintillators in coincidence with the outermost wire chamber provided a trigger. A photograph of the experimental setup is shown in Fig. 1.

Signals from the detectors were amplified and discriminated in standard NIM electronics, were digitized in FERA ADCs, and read into a computer using PCDAC. The detectors measured position to a precision of about 400 μm full width at half maximum (FWHM), and angles to about 2 mrad FWHM.

The data were processed using a simple reconstruction technique that localized the contribution of each muon to a point near the intersection of the incident and outgoing trajectory. This is similar to a nuclear scattering reconstruction technique previously described, but uses multiple scattering rather than single scattering. The length within which the material was localized along the trajectory was a power function of the scattering angle. This localization method does not work for extended geometries of overlapping material but works well for localized scatterers and is good for demonstrating the technique. A reconstructed image with the tungsten slug in the apparatus is shown in Fig. 2. The tungsten is clearly visible as the bright spot in the reconstruction. More complicated reconstruction techniques which use all of the information available in an optimum fashion, under development, can be expected to give even better results.

We have found that in addition to multiple scattering there is also a 15% attenuation of cosmic ray flux in the object. The particles that stop in the object may provide further information. The attenuation signal might be used in conjunction with multiple scattering to increase the significance of the signature of SNM. In addition, since the stopping rate of cosmic rays is larger for lower z materials some composition information might be extracted by comparing the stopping rate with the multiple scattering signatures. Finally, a fraction of the stopped particles are μ-. These are expected to produce muonic x-rays and fissions in high-Z materials. Coincidences between stopped cosmic rays and gamma rays and neutrons may provide distinctive signatures of contraband SNM. Utilizing this information will likely require longer counting times than are anticipated for screening for shielded SNM.

In Fig. 3, the angular distributions for events that pass through the tungsten is compared with that for events that don't (labelled background). The angular resolution of the experiment as given by the width of the background distribution is 3.5 mrad. The simulated scattering in the tungsten is 20 mrad FWHM.

With longer counting times this technique allows details in simple structures to be radiographed. This is illustrated by the radiographs shown in Fig. 4 of some simple objects. The LANL was constructed from 1.9 cm thick lead plate. The C clamp is constructed from steel. Both objects are clearly identified in the radiographs.

Monte Carlo simulations

In order to examine how well this technique works for more complex objects, we have developed a simulation code that generated cosmic-ray muons with the appropriate distribution of energies and angles, propagated them through a test volume, and generated the positions at which they would be detected in four detector planes. The muon spectrum, angular distribution, and rate were appropriate for sea level.

Figure 3 shows a comparison between the Monte Carlo predictions and the data. The good agreement provides a validation of the cosmic ray generator and the multiple scattering model. The background distribution in the simulation is slightly broader in the simulation than in the data. This is likely to be due to a slight over estimate of the detector position resolution in the Monte Carlo model.

We have simulated muons propagating through a 1/8 inch thick steel-walled container that contained high-Z targets ("pigs"), surrounded by dozens of low-Z objects ("sheep"). The input geometry is shown Fig. 5a and a reconstructed image is shown in Figure 5b. The detector pairs, assumed to have our experimental resolution of 0.4 mm (FWHM), are spaced 1 meter apart (h), and spanned a 3 meter high (l) test volume. The "pig" was detected at high confidence in a 1-minute simulated exposure: the signal in the 3 x 3 x 3 voxel core was 55.4 ± 16.1, in arbitrary units, while the background in an adjacent volume was 7.11 ± 1.36. This means that with 90% confidence, we obtain a signal that is inconsistent with background at 20 sigma significance or greater. A typical 1-minute simulation is plotted in figure 4b. In our reconstruction, we ignore muons with momenta greater than 20 GeV/c, because the small "scatter" angles introduced by random measurement errors appeared significant in our momentum-weighted algorithm.

We do not pretend to have found the optimum algorithm for reconstruction. Indeed, when we simply ignore all rays with a scatter angle less than 5 mrad, the 90%-worst-case significance of detection increases from 20 sigma to better than 29 sigma. Reconstruction methods that use all of the information in the transmitted muon trajectory which are expected to provide an even more significant signal are under development.

Implementation

In summary simple calculations, supported by simulations, indicate that this technique can detect the presence of a compact package on the order of 20 kg of shielding and SNM with a signal to noise level of greater than 20 standard deviations with about 60 seconds of counting time, using only naturally occurring cosmic radiation. A drawing, illustrating how this idea might be implemented at a border crossing, is shown in Fig. 6.

A rough idea of the cost of such a station can be obtained using estimates based on building large area detectors for high energy physics. An element of the detector would consist of 5 cm diameter aluminum tube with a small diameter (20 μm) wire running down its axis. A positive voltage on the wire would attract electrons to the wire provide amplification of the ionization produced in the gas within the tube by a passing cosmic rays. Drift time information (the time it takes for the electrons produced by ionizing the gas to reach the wire) would be used to localize positions within the detector volume. Similar information for an adjacent, but offset plane would be used to resolve the finite drift direction ambiguity. Orthogonal planes will be needed to obtain information from both coordinates. Alternately x-u-v planes may provide the needed redundancy at lower cost. Although most of the layers would consist of two offset rows of drift tubes, a triple layer of tubes could be used to establish the timing.[11]

The dominant costs of such detectors are in the readout and the mechanics at the end of the tubes, and so cost scales like the perimeter length. We estimate the cost of a single coordinate measurement will be about $100/cm, including both planes needed to fully reconstruct the drift time information. The cost of the six planes needed to measure both incoming and outgoing trajectories for an automobile sized counting station, 8 m by 5 m, would be about $\$1.5\text{x}10^6$.

There are several differences between this application and a physics experiment. Cosmic ray counting rates are low when compared with most high energy physics experiment. Consequently, counter lifetimes can reasonable expected to be long (decades). On the other hand, the large inexpensive skilled workforce required to maintain a high energy detector will not be available at border crossings. Detectors will need to require little or no maintenance in potential harsh environments. We are investigating using sealed aluminum walled drift tubes to assure robust, low maintenance detectors.

This technique provides the potential to examine every vehicle and shipping container crossing the US (or foreign) border. All that is needed is enough detectors at border crossing to handle the traffic. Using statistics compiled by the US department of transportation, the total person-vehicle cross US-Mexico and US-Canada border traffic was 1.3×10^8 for the year 2000 (probable the highest volume surreptitious entry route).[12] If a single radiography machine can analyze a vehicle within 60 seconds of counting/processing time, operating for 12 hours per day, than only about 500 machines would be needed to handle the entire cross border personal vehicle load. (In order to accomplish this goal, one presumably needs to take advantage of the time that vehicles are entering and exiting the machine, and processing will need to occur within the same time window. This has not yet been demonstrated.) The total cost of $\$750 \times 10^6$ is clearly negligible when compared with the economic consequence of the detonation of a nuclear device within the US borders. Queuing times may require doubling this estimate. A smaller size effort would be need to handle commercial cross border truck and sea port transportainers traffic. We do not yet have estimates of maintenance and replacement costs for continuous operation.

The same technique can be used to examine cargo in trucks and transportainers. The long storage time of transportainers in transit in ships at sea suggests a possibility. Special transportainers containing position sensitive detectors could be interspersed with normal cargo. Radiography could be accomplished using coincidence between these monitor transportainers, to sample the cargo in the hold of the ship. Although this technique might not afford 100% coverage, it could take advantage of the transport time to survey some of the cargo in a ship.

Conclusion

A technique for radiographing large objects with cosmic muons has been described. This technique is particularly sensitive to high-Z dense materials. We have shown it can provide a method for detecting smuggled cargoes of SNM in incoming vehicles and commercial traffic at US borders with no additional radiation dose to vehicle occupants or border guards. Experimental and Monte Carlo demonstration of this technique both show that it provides significant signatures (20 standard deviations) in short (30 sec) counting times. A rough cost estimate for the capability of searching every incoming passenger vehicle ($\$750 \times 10^6$) shows the technique to economically viable.

Publications

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Figure Captions

Fig. 1. The experimental apparatus. The scattering object is a tungsten cylinder (density 18.5) 11 cm in diameter and 5.7 cm in height.
Fig. 2. Muon radiograph of a 60 x 60 x 30 cm test volume containing a tungsten test object, based on experiment a) and a simulation b). The tungsten scatter is unambiguously observed. In addition, the unistrut rails supporting the tungsten object are observed.
Fig. 3. The red line shows the projected angular distribution for events that pass through the tungsten cylinder for the experiment (bottom) and the simulation (top). The blue line shows the angular distribution for events that don't pass through the tungsten
Fig. 4. panels a and b show pictures and c and d show radiographs of some objects which illustrate the ability to resolve details in muon radiography.
Fig. 5. Panel a) shows the Monte Carlo set up; panel b) the reconstruction. The pigs are the bright spots in both panels. The lowest pig is the most difficult to observe because it is at the edge of the detector acceptance. (This problem is easily fixed with slightly large detectors.)
Fig. 6. A schematic view of how a counting station might look. In addition to the detectors needed to measure the incoming and outgoing trajectories, there are two extra layers, separated

by steel plates for measuring the muon energy to low precision. Vehicles would be stopped within the area covered by the counting station for the counting period.

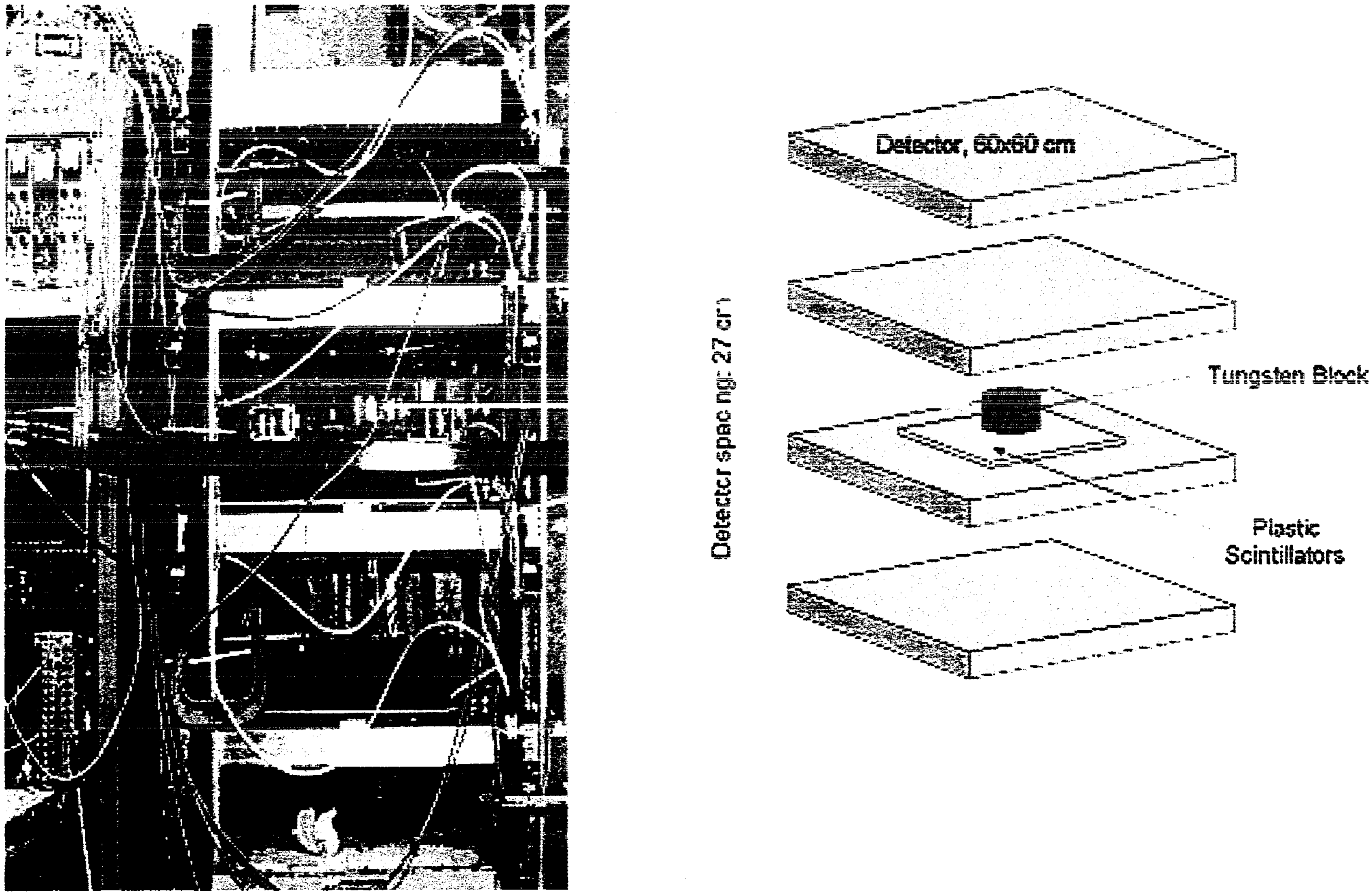
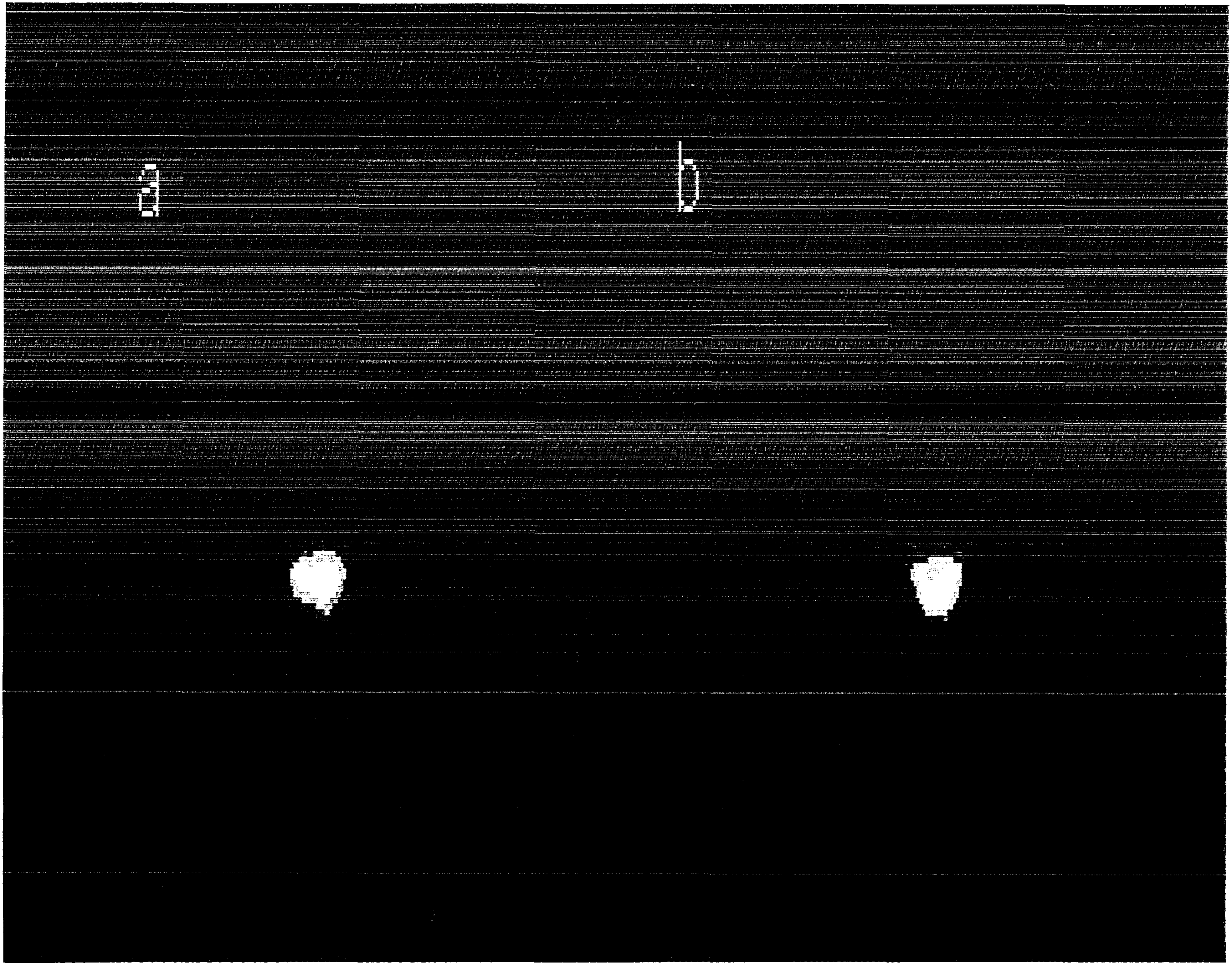

Detector, 60x60 cm
Tungsten Block
Plastic Scintillators
Detector spacing: 27 cm

FIGURE 1


a
b

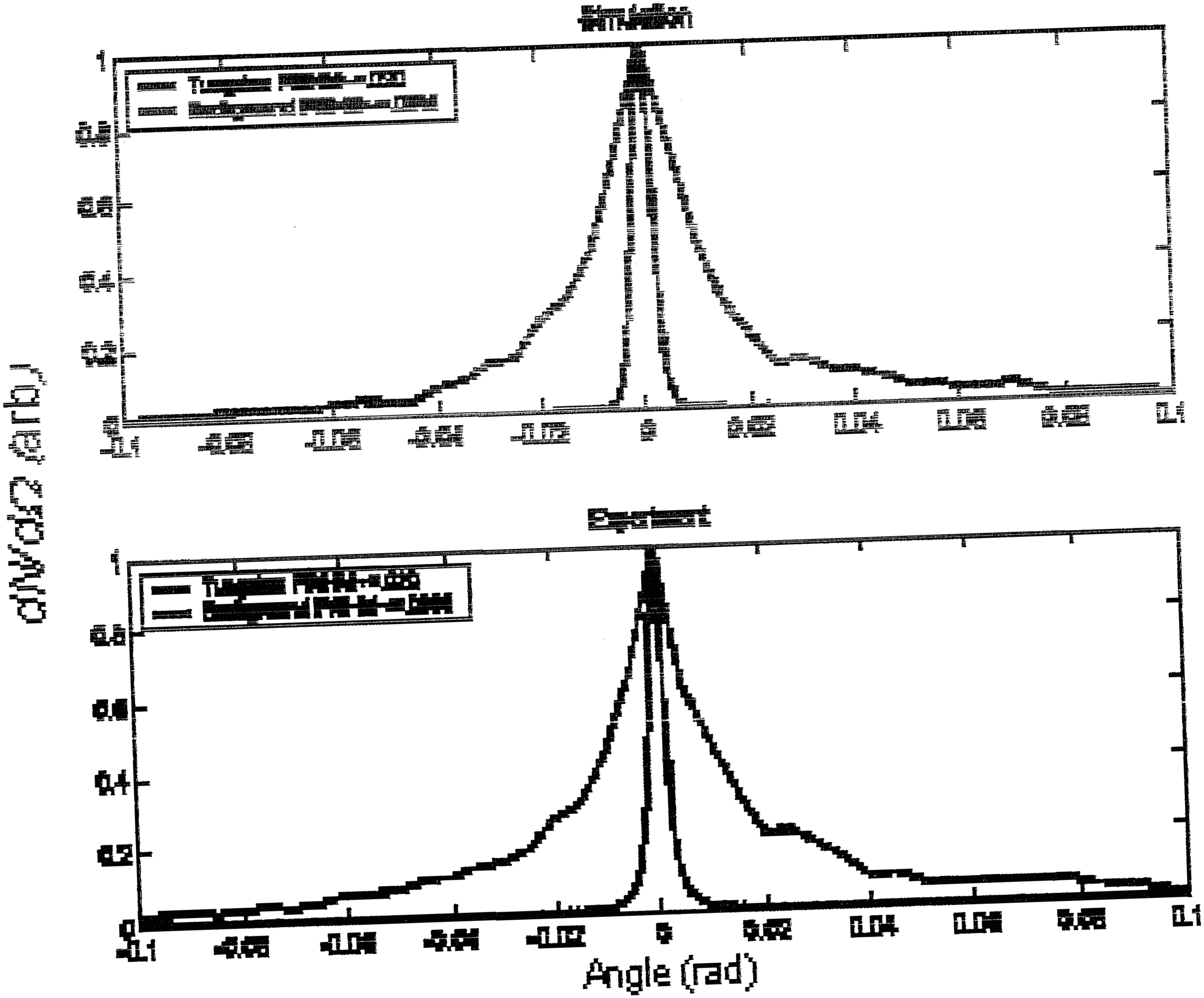


FIGURE 3

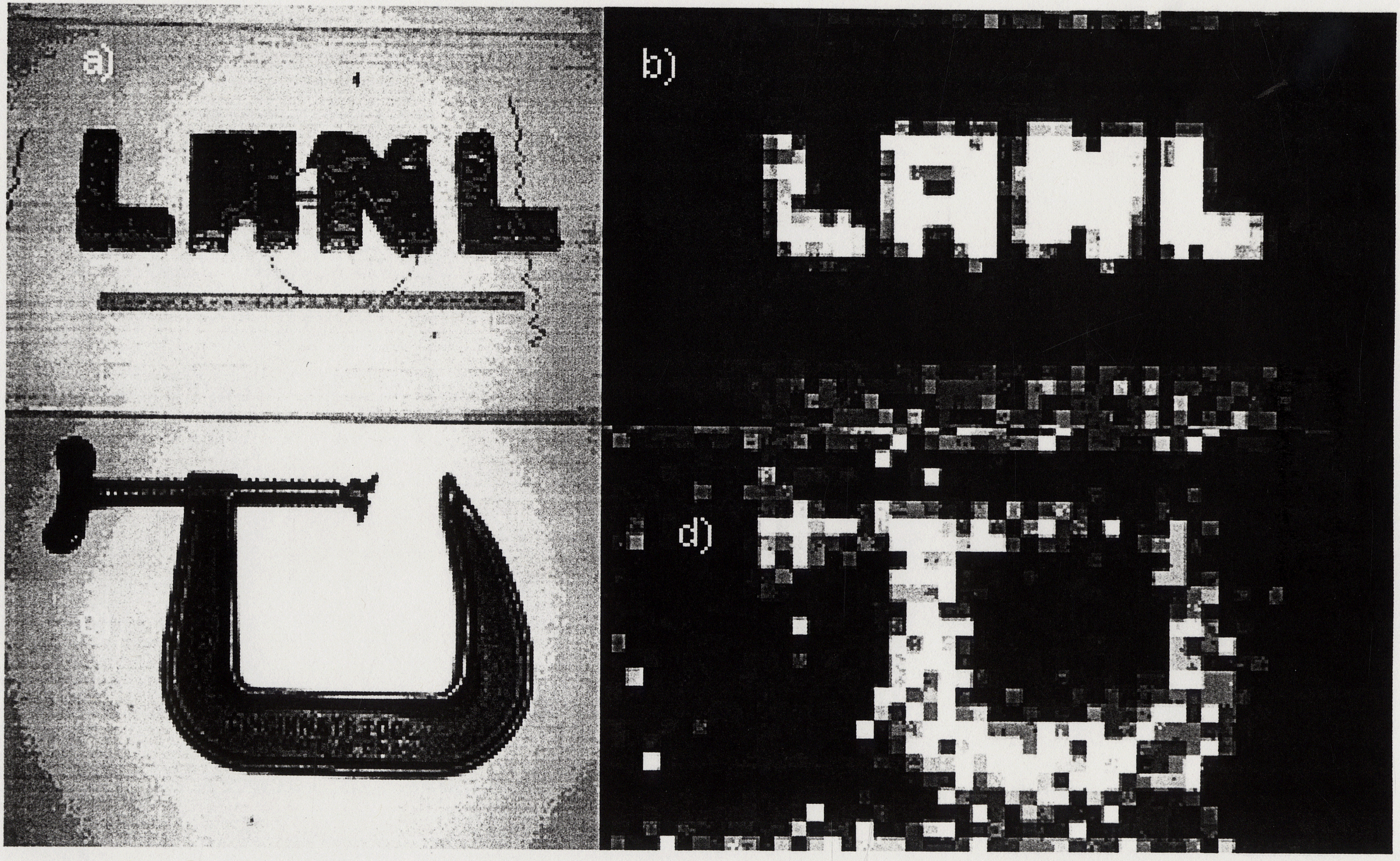
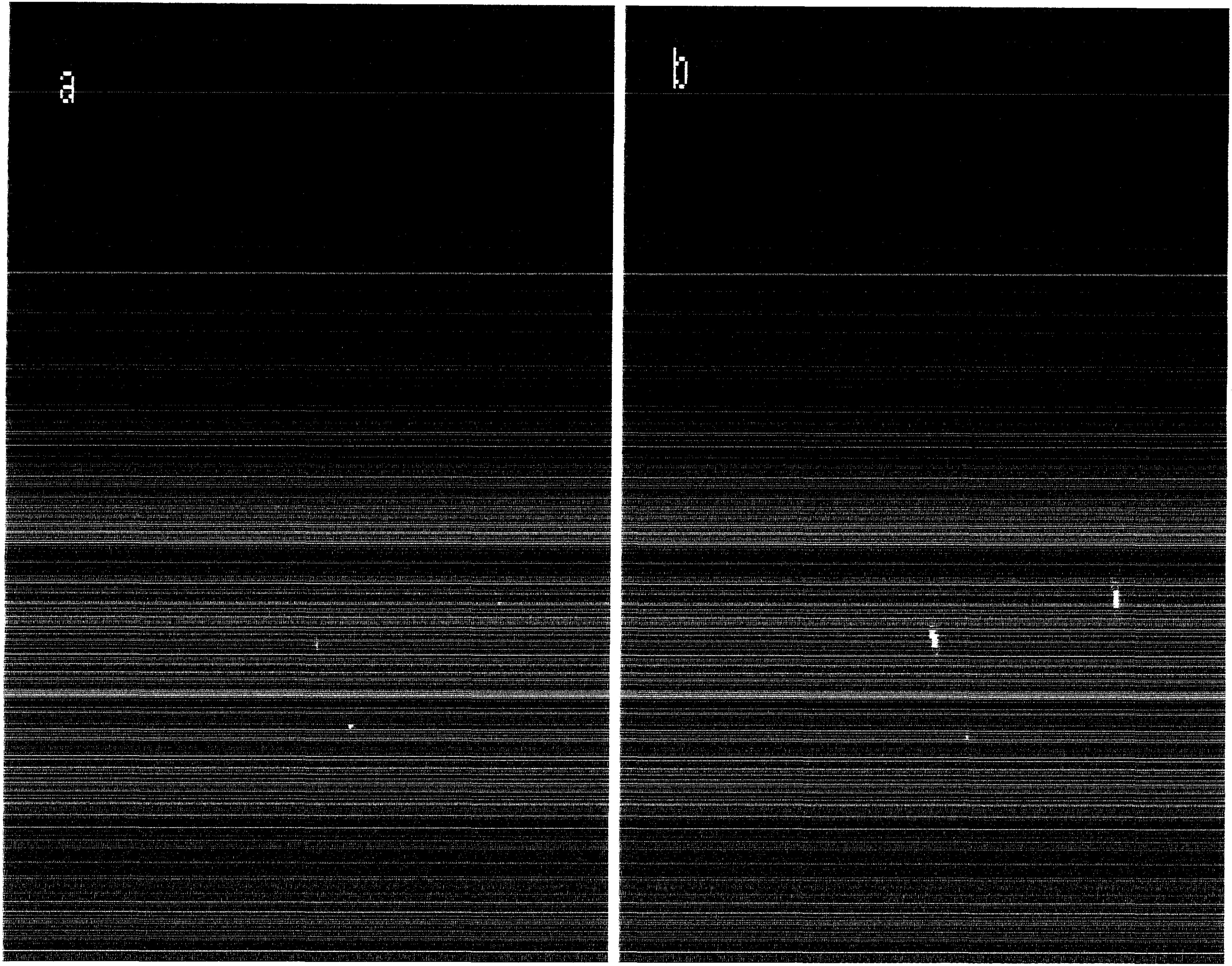


FIGURE 4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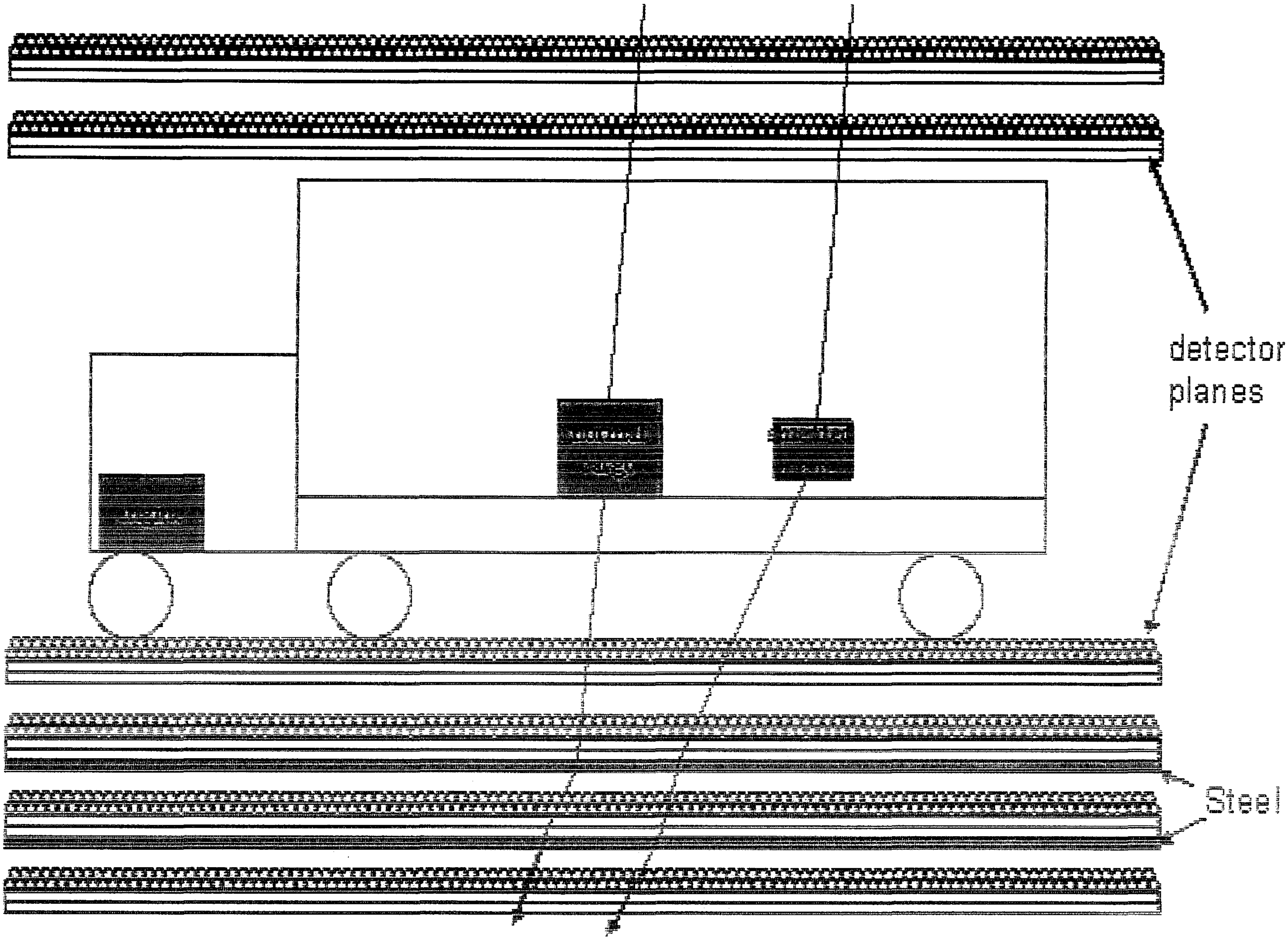

FIGURE 6